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# CONTROL LAW DESIGN TO MEET CONSTRAINTS USING SYNPAC--SYNTHESIS PACKAGE FOR ACTIVE CONTROLS

William M. Adams, Jr. and Sherwood H. Tiffany

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**Langley Research Center**
Hampton, Virginia 23665

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## SUMMARY

Major features of SYNPAC (Synthesis Package for Active Controls) are described. SYNPAC employs constrained optimization techniques which allow explicit inclusion of design criteria (constraints) in the control law design process. Interrelationships are indicated between the constrained optimization approach, classical and LQG (linear quadratic gaussian) design techniques. Results are presented that were obtained by applying SYNPAC to the design of a combined stability augmentation/gust load alleviation contol law for the DAST ARW-2 (Drones for Aerodynamic and Structural Testing, 2nd Aeroelastic Research Wing). A 34.5% reduction in the standard deviation of incremental wing root bending moment was achieved within available control power with satisfactory short period dynamics.

## INTRODUCTION

A description will be given of techniques employed in SYNPAC. The development of SYNPAC is an in-house activity. Existing algorithms are being employed whenever possible and the authors are benefiting from the efforts of other researchers (Refs. 1 through 9).

The paper will cover three areas:

1. The motivation for utilization of constrained optimization techniques in control law design will be discussed. Interrelationships between the constrained optimization approach and classical and LQG design techniques will be indicated.

2. The manner in which the constrained optimization approach is implemented in SYNPAC will be illustrated by stepping through a computational flow diagram.

3. Results will be presented that were obtained using SYNPAC in the design of a combined RSS/GLA (relaxed static stability augmentation/gust load alleviation) control law for a drone aircraft.

## MULTIOBJECTIVE CONTROL LAW DESIGN

One basic control law design problem is that a number of often conflicting objectives or constraints must be met. Reference 2 is an example of the application of the philosophy that one should explicitly include the constraining relationships in the design process. Therein constrained optimization techniques were employed to allow explicit consideration of handling quality constraints for the lateral degrees of freedom of a rigid fighter aircraft.

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Constrained optimization techniques are also employed in SYNPAC for design of active control laws. The number and importance of design criteria has increased with the application of active controls. Control laws may now be required to provide load alleviation, flutter suppression and stability which were formerly inherent characteristics of the aircraft. A partial list of design criteria or constraints that might be required for an actively controlled aircraft follows:

- Satisfactory Handling Qualities
- Load Alleviation
- Elastic Mode Stabilization
- Minimum Control Power
- Robustness

## Interrelationships of Design Techniques

Next, a brief description will be given of the interrelationship between constrained optimization and other more commonly employed techniques. The constrained optimization approach of SYNPAC has the advantage that, if a solution is found, it is satisfactory provided all pertinent constraints have been considered. It has some disadvantages. Iterative methods are required to obtain a solution; also, the form of the control law must be specified in advance.

A fixed form control law is precisely what one would have in feedback of compensated signals developed using classical frequency domain techniques. For a multi-input/multi-output design one might have compensation of the following form for each control/sensor pair.

$$\frac{K_{ij}\left(A_{0_{ij}} + A_{1_{ij}} s + \ldots + A_{m_{ij}} s^{m_{ij}}\right)}{\left(B_{0_{ij}} + B_{1_{ij}} s + \ldots + s^{n_{ij}}\right)}$$

where the overall gains and polynomial coefficients are free parameters. In the classical approach one typically closes one loop at a time. In contrast, SYNPAC solves simultaneously for the free parameters in a multiple-input/multiple-output control law provided a control law form can be specified. The resulting solution optimizes a measure of performance subject to stipulated constraints. The results presented subsequently illustrate this type of application of SYNPAC.

Consideration of constraints is often indirect in design using LQG techniques, accomplished through appropriate choices of weighting matrices in the performance function. Furthermore, simplification of LQG designs is often required prior to implementation. Consequently, a reduced order controller having fixed order and, therefore, a fixed number of free parameters is sought (Refs. 10, 11 and 12). SYNPAC could be employed to find the best set of parameters in such a reduced order controller while explicitly considering the design criteria.

The constrained optimization approach of SYNPAC is complementary to both classical and LQG design techniques. It automates the search for the free parameters in a candidate classical design and can be employed to simplify an LQG design while, in each case, explicitly considering the constraints. Reference 13 develops,

in more depth, the philosophy for an LQG/constrained optimization approach and presents an example of its implementation.

## Computational Flow in SYNPAC

Figure 1 illustrates the SYNPAC design process. First a set of design constants are input defining the open loop model, including sensor and actuator dynamics. The form of the control law is specified, obtainable from frequency domain considerations, simplification of an LQG design or, perhaps, from experience with a similar configuration. Constraints which the final design must satisfy are specified. These may include handling qualities, maximum achievable control surface deflections and rates, maximum allowable loads, degree of stability, etc.

The search for an acceptable design is initiated by input of an estimate for the design variables. For the results shown in this paper, the design variables are limited to feedback gains and filter coefficients. The closed loop stability and response characteristics are evaluated, using an analysis module (Ref. 1), and compared with the design criteria. Any deficiencies are noted. A performance function or figure of merit is chosen from among the design criteria and is employed to evaluate the goodness of the design. For this study, RMS incremental wing root bending moment (RMS-WRBM) was chosen as the performance function. An augmented function is formed composed of RMS-WRBM and the effects of any constraint violations. This augmented performance function is fed to a nonlinear programing algorithm which determines how to step, simultaneously, in all design variables so as to lower RMS-WRBM and reduce any constraint violations. This process is repeated iteratively until a solution is found which meets all the design objectives. If no solution is found, one must relax constraints and/or choose an alternate control law.

The nonlinear programing algorithm employed in this study was the Nelder-Mead simplex (Refs. 8 and 9), a nongradient-based method which required an initially feasible solution.

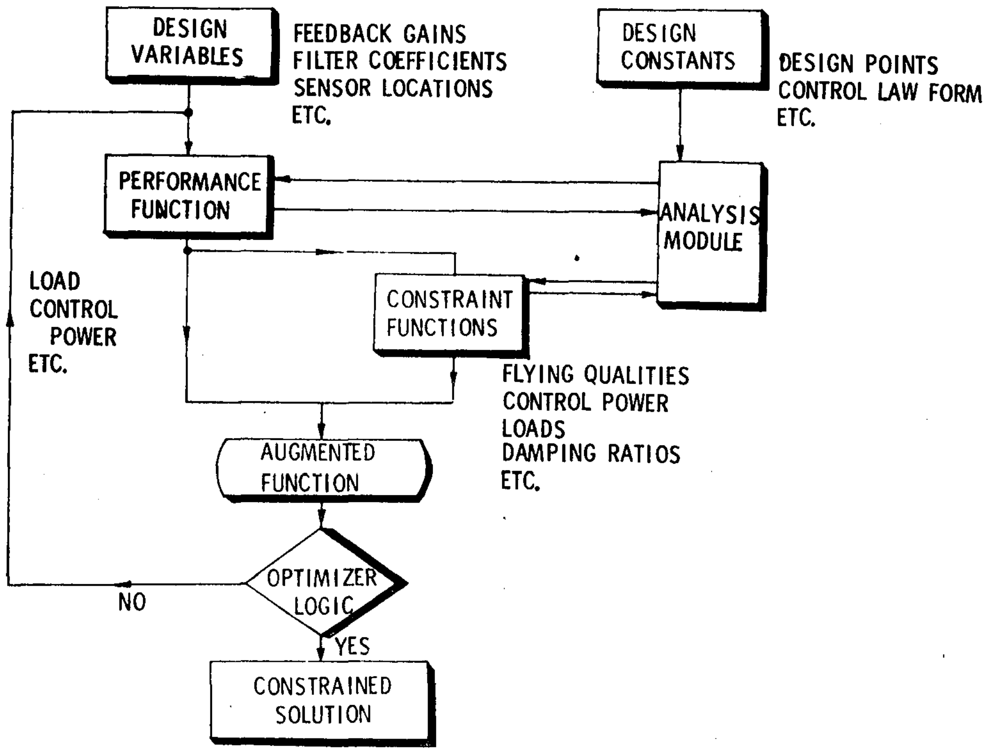


Figure 1.- Synthesis Package for Active Controls (SYNPAC).

## MATHEMATICAL MODELING OF DAST ARW-2 WITH CONTROLS

SYNPAC has been employed in the design of a combined relaxed static stability augmentation/gust load alleviation control law for the DAST ARW-2. This aircraft has been designed to require several active control functions for safety of flight in some regions of its flight envelope (Ref. 14). This section indicates some of the assumptions and approximations made in carrying out the design.

Results have been obtained at only one, gust critical, flight condition; no investigation has been made of the need for gain scheduling. The mathematical model used for control law evaluation included 2 rigid body and 10 symmetric elastic modes. The equations of motion have the following form:

$$\left[\left(M_{ii}s^2+D_{ii}s+K_{ii}\right)e_{ij}-\bar{q}\ A_{ij}(s)\right]\begin{Bmatrix} z \\ \theta \\ q_e \end{Bmatrix} = \bar{q}\ A_\delta(s)\delta+\bar{q}\ A_{w_g}(s)w_g$$

which can be rewritten as

$$H(s)q = B(s)\begin{Bmatrix} \delta \\ w_g \end{Bmatrix} = B(s)u \qquad (1)$$

actuator $\delta = T_A(s)\delta_c$ (2)

control law $\delta_c = T_L(s)y$ (3)

output $y = C(s)q.$ (4)

In these equations

| | |
|---|---|
| n,nc,ns | number of generalized coordinates, control surfaces and sensor outputs, respectively |
| $q, \delta, y$ | vectors of generalized coordinates, controls and sensor outputs, respectively |
| z | rigid body vertical motion (+ up) |
| $\theta$ | rigid pitch about center of mass (+ nose up) |
| $q_e$ | vector containing elastic generalized coordinates, (n-2)x1 |
| $w_g$ | vertical gust velocity (+ up) |
| $\bar{q}$ | dynamic pressure |
| $e_{ij}$ | 1 if i=j, 0 if i≠j |
| m | airplane mass |
| M | generalized mass matrix ($M_{22}$ is pitch moment of inertia about the center of mass), nxn |
| K | generalized stiffness matrix ($K_{11} = 0$, $K_{22} = 0$), nxn |
| D | structural damping, modeled as viscous ($D_{11} = 0$, $D_{22} = 0$), nxn |
| A | generalized aerodynamic force matrix, nx(n+nc+1) |
| $T_A$ | diagonal matrix containing actuator dynamics, ncxnc |
| $T_L$ | matrix of transfer functions relating desired control position to sensor output, ncxns |
| C | matrix relating sensor outputs to generalized coordinates, nsxn |

A smaller mathematical model was employed in performing the control law design; a residual stiffness approximation (ref. 15) was used to obtain a model which retained two rigid body and three elastic modes. The generalized coordinates were divided into two vectors. The vector $\hat{q}_1$ contained rigid vertical displacement, pitch and elastic modes that were the first (lowest frequency), third and fourth primarily wing modes. The vector $\hat{q}_2$ contained the second primarily wing mode which was fore and aft in character, fuselage modes and higher frequency modes. Only the static effects of $\hat{q}_2$ upon $\hat{q}_1$ were retained. This was accomplished by the following approximations in equations (1) and (4).

$$\begin{bmatrix} H_{11}(s) & H_{12}(0) \\ H_{21}(s) & H_{22}(0) \end{bmatrix} \begin{Bmatrix} \hat{q}_1 \\ \hat{q}_2 \end{Bmatrix} = \begin{bmatrix} B_1(s) \\ B_2(s) \end{bmatrix} u \qquad (5)$$

and

$$\hat{y} = C_1(s)\hat{q}_1 + C_2(0)\hat{q}_2 \qquad (6)$$

When the second block of rows of equation 5 are solved for $\hat{q}_2$, the following residualized equations are obtained by back substitution.

$$\hat{H}(s)\hat{q}_1 = \hat{B}(s)u \tag{7}$$

$$\hat{y} = \hat{C}(s)\hat{q}_1 + \hat{E}(s)u$$

where

$$\hat{H}(s) = H_{11}(s) - H_{12}(0)H_{22}^{-1}(0)H_{21}(s)$$

$$\hat{B}(s) = B_1(s) - H_{12}(0)H_{22}^{-1}(0)B_2(s)$$

$$\hat{C}(s) = C_1(s) - C_2(0)H_{22}^{-1}(0)H_{21}(s)$$

$$\hat{E}(s) = C_2(0)H_{22}^{-1}(0)B_2(s)$$

Effectiveness factors, developed by Boeing Wichita to force agreement with Flexstab (Ref. 16) quasi-static elastic stability and control derivatives (used here with permission from Boeing), were applied to local downwash and pressure terms employed in the doublet lattice code for generating unsteady aerodynamic forces. Substantial reductions in the effectiveness of wing control surfaces resulted as compared with what was predicted using unity effectiveness factors. In contrast, unity effectiveness factors were employed in the study described in reference 13.

Unsteady aerodynamic forces were then modeled using an s-plane approximation in order to facilitate determination of eigenvalues. The approximation was of the form employed in reference 5. Two lag terms were used in the s-plane approximation. The loads computations were performed in the frequency domain. Consequently, the s-plane approximation was not used in the loads computations.

## Error in Moments Due to Residualization (Open Loop)

Residualization resulted in errors of only 0.2% and -0.3% in incremental wing root bending and incremental wing root torsion, respectively. Truncation retaining the same generalized coordinates resulted in -4% and -44% errors in bending and torsion, respectively.

## Normalized Power Spectral Density of Incremental Wing Root Bending Moment Per Unit RMS Input Gust Velocity

Some open loop characteristics are presented which illustrate the frequency characteristics of WRBM due to gusts. Figure 2 is presented to give a rationale for both the choice of sensors in the RSS/GLA control law and the use of the stabilizer as a wing load alleviation device. The power contributed to bending due to gust inputs, assuming a Von Karman spectrum, is concentrated in the rigid body frequency

range. There is no appreciable contribution in the elastic mode frequency range. Consequently, one might anticipate that sensors near the center of mass and the stabilizer, in addition to wing control surfaces, might be effective for WRBM alleviation. The large separation in frequency between the rigid body and elastic eigenvalues is a consequence of the small size of the ARW-2.

The normalization factor employed in the figure is 9893 $\left(\frac{\text{N-m}}{\text{m/sec}}\right)^2$, $\left(500 \left(\frac{\text{in-lb}}{\text{in/sec}}\right)^2\right)$

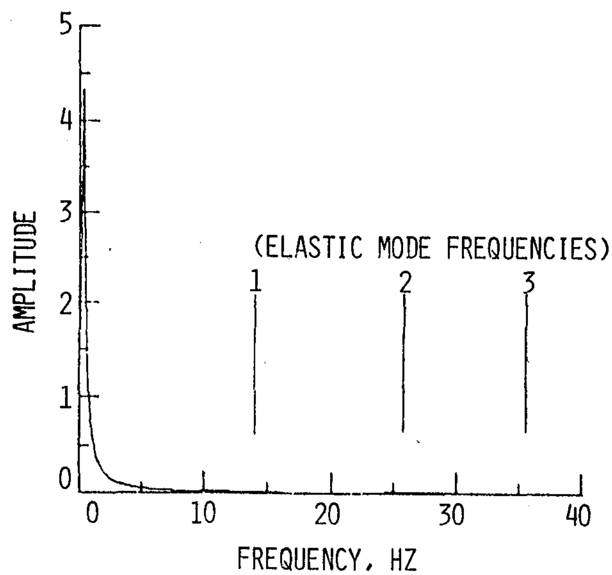


Figure 2.- Normalized Power Spectral Density of Wing Root Bending Moment Per Unit RMS Input Gust Velocity.

### DAST ARW-2 Sensor and Control Surface Locations

Figure 3 illustrates the sensors and control surfaces employed in the RSS/GLA control law. Pitch rate and incremental acceleration were fed back from a point near the center of mass. Control surfaces employed were outboard aileron, stabilizer and two inboard aileron segments (driven as one surface). Roll control, not considered in this study involving symmetric modes, is achieved through differential deflection of the horizontal stabilizers.

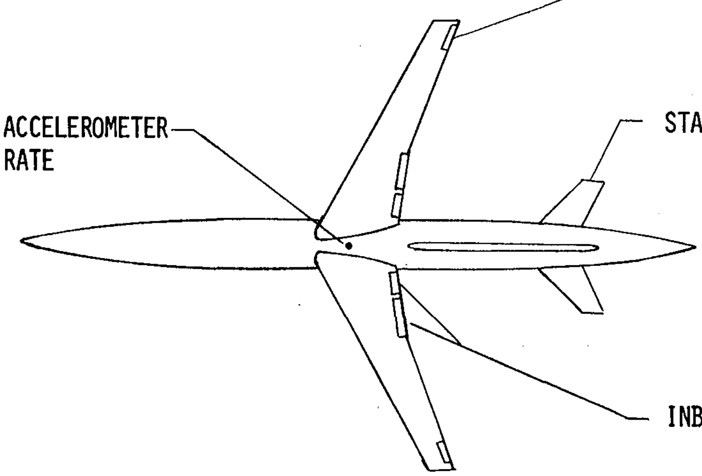


Figure 3.- DAST ARW-2 Sensor and Control Surface Locations.

## RSS/GLA System Block Diagram

Figure 4 defines the form of the control law. In the load alleviation loop, incremental acceleration is fed back to each control surface. In the RSS loop, pitch rate is fed back to the stabilizer only. The filters between sensors and stabilizer and outboard ailerons are similar in form to control laws developed by Boeing Wichita. Boeing did not include the inboard ailerons in their GLA control law; however, in this study the inboard ailerons have been employed for GLA.

The functions $T_i(s)$, i=1 to 4 are fixed filters primarily composed of low pass elements to attenuate high frequency components of the sensor signals; $T_4(s)$ also contains lead/lag elements which amplify the signal at very low frequencies. The overall characteristics of the filter between incremental acceleration and the stabilizer, excluding $K_3$, are unit magnitude at low frequency, little phase shift up to $\omega \approx b$, large gain at $\omega \approx b$ and rapid attenuation at high frequencies.

Maneuver load alleviation (MLA) is not included in this study; however, the wing control surfaces will ultimately be employed to provide maneuver load alleviation. The high pass filter, $\frac{s}{s+9.5}$, was included in the loop to the inboard ailerons to null out low frequency signals because commanded deflections for GLA would oppose the lift generation signal required in a MLA control law. The moment generated by a steady state deflection of the stabilizer due to incremental acceleration should balance the pitching moment due to steady deflection of the wing control surfaces. This constraint on $K_3$ was not included.

The parameters that were variable in the design were the four feedback gains and a, b, and c.

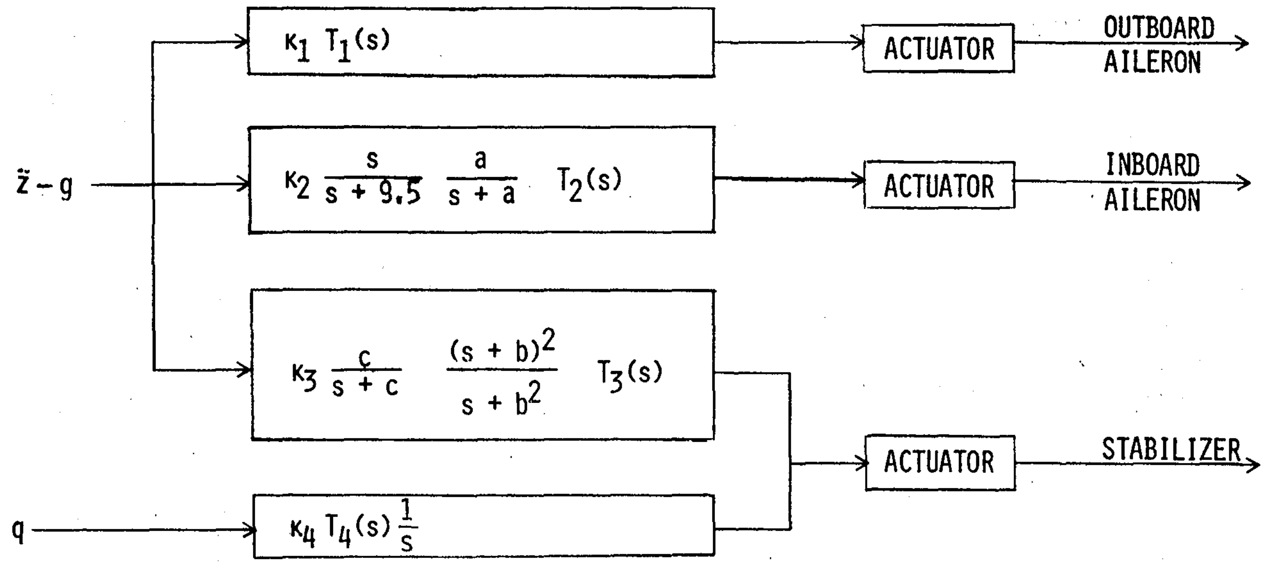


Figure 4.- RSS/GLA System Block Diagram.

### Control System Design Constraints

The constraints imposed in this study are listed below. Handling qualities are considered approximately by including requirements on the short period eigenvalue.

- Minimize RMS Incremental Wing Root Bending Moment
- Limit Increase in RMS Incremental Wing Root Torsion to 25%
- Short Period Damping Ratio > 0.3
- Short Period Natural Frequency < 11.3 rad/sec
- Elastic Mode Damping Ratios > 0.015
- No Control Displacement or Rate Saturation in an RMS Sense for an 18 m/sec (59 ft/sec) RMS Gust Input

## RESULTS

### Design and Constraint Variables

Tables 1 and 2 depict the values found by SYNPAC for the design and constraint variables. Note that stabilizer rate, outboard aileron displacement, inboard aileron rate and RMS incremental wing root torsion are active constraints (closer to their constraint boundaries than 3% of their permissable range of values.)

A precise local optimum was not sought. Consequently, slight additional improvements in performance could be obtained and the set of active constraints might change if the iterative search were continued.

Table 1.- Design Variables

| a 1/sec | b 1/sec | c 1/sec | $K_1$* deg/g | $K_2$ deg/g | $K_3$ deg/g | $K_4$ sec |
|---|---|---|---|---|---|---|
| 24.64 | 6.537 | 46.69 | -18.87 | -6.194 | 0.9425 | 2.005 |

*Another optimization was performed with the constraint that $|K_1| \leq 10$ deg/g. The ($\sigma$-WRBM) reduction found was only 0.5% less (relative to the open loop value) than found for the case presented here. The stabilizer provides most of the gust load alleviation.

Table 2.- Constraints.

| Variables | Values | Lower Boundary | Upper Boundary |
|---|---|---|---|
| $\delta_{S_{rms}}$ | 3.753 deg | 0 | 5 deg |
| $\dot{\delta}_{S_{rms}}$ | 78.55 deg/sec | 0 | 80 deg/sec |
| $\delta_{OA_{rms}}$ | 15.10 deg | 0 | 15 deg |
| $\dot{\delta}_{OA_{rms}}$ | 143.5 deg/sec | 0 | 710 deg/sec |
| $\delta_{IA_{rms}}$ | 5.235 deg | 0 | 10 deg |
| $\dot{\delta}_{IA_{rms}}$ | 97.59 deg/sec | 0 | 100 deg/sec |
| Wing Root Torsion (% of open loop) | 123.6 | 0 | 125 |
| $\zeta_{SP_{rms}}$ | 0.6046 | 0.3 | 1.00 |
| $\omega_{n_{SP_{rms}}}$ | 9.287 rad/sec | 2.5 | 11.30 rad/sec |

Normalized Power Spectral Density of Incremental Wing Root Bending Moment Per Unit RMS Input Gust Velocity

Figure 5 shows the effect of the control law upon the power spectral density of incremental wing root bending moment. The closed loop power spectral density is substantially attenuated in the rigid body frequency range with no apparent excitation at higher frequencies.

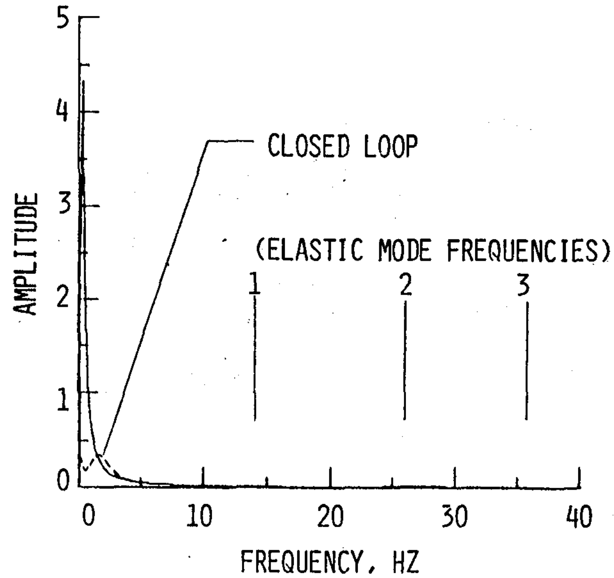


Figure 5.- Normalized Power Spectral Density of Incremental Wing Root Bending Moment Per Unit RMS Input Gust Velocity.

Normalized Power Spectral Density of Incremental Wing Root Torsional Moment Per Unit RMS Input Gust Velocity

Application of the control law increased wing root torsion as can be seen in Figure 6 in the short period frequency range. There was little excitation at higher frequencies. The increase in torsion was within the specified design criterion of 25%.

The normalization factor employed in this figure is 98.93 $\left(\frac{\text{N-m}}{\text{m/sec}}\right)^2$, $\left(5 \left(\frac{\text{in-lb}}{\text{in/sec}}\right)^2\right)$.

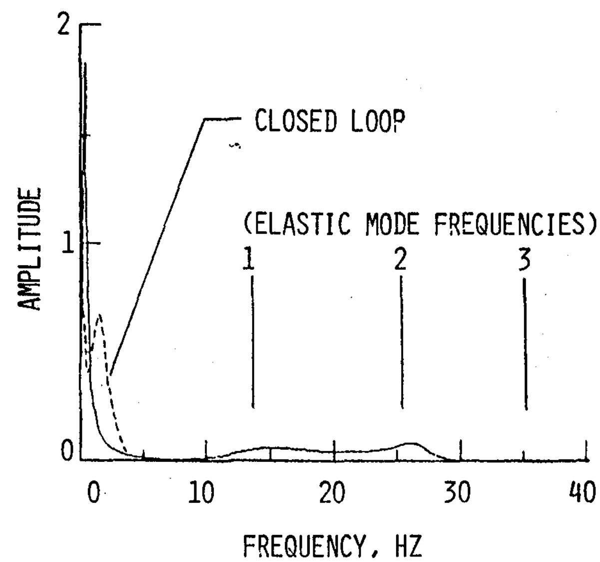


Figure 6.- Normalized Power Spectral Density of Incremental Wing Root Torsional Moment Per Unit RMS Input Gust Velocity.

Spanwise Variation of Incremental Bending Moment

Figure 7 shows how the incremental bending moment varies with span for the open and closed loop cases. The reduction achieved with the control loops closed is due partly to lift redistribution resulting from deflection of the wing control surfaces. However, most of the reduction is due to the movement of the stabilizer so as to counter the effect of the added lift due to the gust.

The normalization used in the figure is 1130 N-m (10000 in-lb). The wing semispan is 2.8936 m (113.92 in).

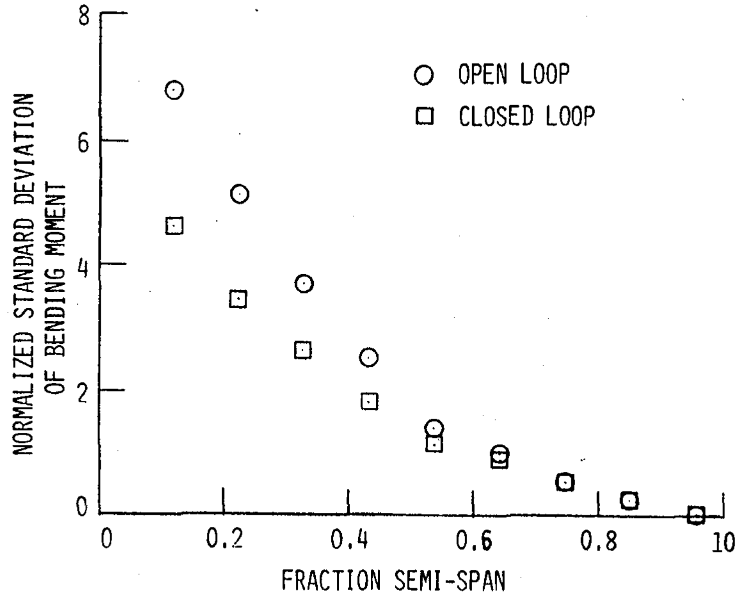


Figure 7.- Normalized Standard Deviation of Incremental Bending Moment Versus Span for a Von Karman Gust Spectrum Having an 18 m/sec (59 ft/sec) RMS Input Gust Velocity.

Control System Performance

A reduction in the standard deviation of incremental wing root bending moment ($\sigma$-WRBM) of 34.5% was achieved using optimization when the stabilizer and inboard and outboard ailerons were employed for load alleviation. When an optimization was performed without employing the inboard ailerons, a 27.5% reduction was achieved. For this two-control case, stabilizer rate and deflection of the outboard ailerons were active constraints.

This example demonstrates the successful application of constrained optimization techniques to the design of a multi-input/multi-output control law.

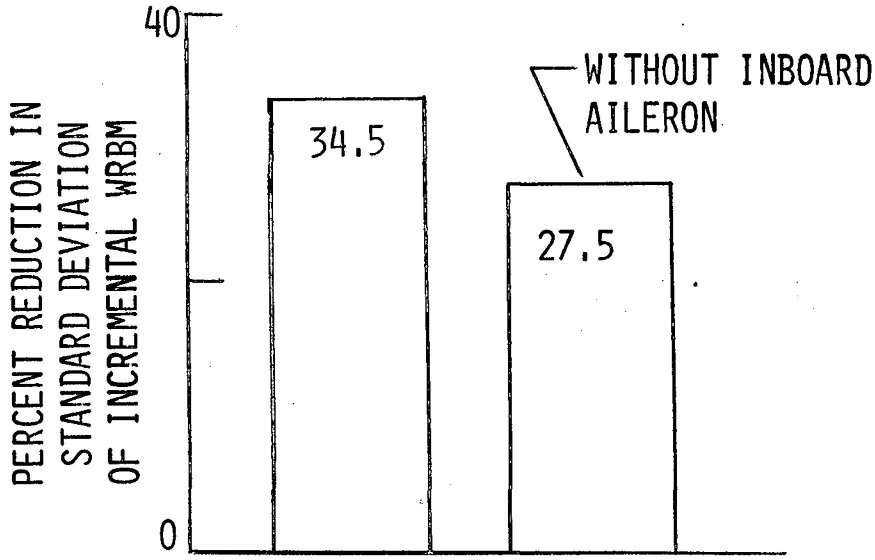


Figure 8.- Control System Performance.

Error in Moments Due to Residualization
(Closed Loop)

Closed loop performance was evaluated using the 2 rigid body, 10 elastic mode model. This investigation revealed that the residualized closed loop model predicted incremental wing root bending moment to within 0.2% and incremental wing root torsion to within 0.5%. Control activity was also virtually identical for the full and the residualized models provided that a prefilter was added in the full model to remove sensor inputs in a narrow frequency band corresponding to a mode in $q_2$ that is primarily first fuselage bending.

## FUTURE ACTIVITY

A study is planned in which SYNPAC will be employed to design a flutter suppression control law for the DAST ARW-2. In addition, a direct tie between SYNPAC and ORACLS (Ref. 17), a software tool containing LQG algorithms, will be implemented to facilitate the use of SYNPAC in the simplification of control laws developed using LQG techniques. Finally, SYNPAC will be documented in about one year, so that it can be distributed through COSMIC.

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